

Investigating the QCD phase diagram with hadron multiplicities at NICA

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Abstract. We discuss the potential of the experimental programme at NICA to investigate the QCD phase diagram and particularly the position of the critical line at large baryon-chemical potential with accurate measurements of particle multiplicities. We briefly review the present status and we outline the tasks to be accomplished both theoretically and the experimentally to make hadronic abundances a sensitive probe.

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1 Introduction

The determination of the critical line of QCD is one of the principal goals of relativistic nuclear collisions. It is especially so in the energy range covered by the NICA experimental programme where one cannot rely on first principle calculations and one would like to identify the supposed critical point. Indeed, the nucleon-nucleon centre-of-mass energy range $\sqrt{s_{NN}}$ between few and 10 GeV, corresponds, according to most extrapolations [1,2,3] to a baryon chemical potential at chemical freeze-out between 300 and 800 MeV, a range which is hardly accessible to lattice QCD owing the notorious sign problem.

The two main questions to cope with, in the NICA energy range, are:

1. has the colliding system thermalized and crossed the critical line?
2. what is the hadronic observable best suited to probe the crossing?

In order to answer these questions, one can, of course, take advantage of the accumulated evidence and knowledge about hadron formation in nuclear collisions at higher energy as well as in elementary collisions. What we have learned from all the previous experience is that hadron formation is basically a universal local statistical process with some remarkable difference in the strangeness sector, whose phase space appears to be only partially filled in elementary collisions [4,5]¹. The salient feature of relativistic nuclear collisions is thus the production - at hadronization - of a fully equilibrated hadronic system whilst in e.g.

e^+e^- or pp collisions strange particles do not saturate the available phase space. The deep reason of these behaviour is still unsettled and its meaning under debate, but for practical purposes this evidence may be used to probe the crossing of the critical line under the reasonable assumption that hadronization coincides with it. In other words, if the hadron production process in a nuclear collision was fully consistent with a picture of subsequent and independent elementary hadronic reactions (like in the hadronic transport models), hence with a - most likely - relatively large undersaturation of strangeness, there would be no reason to claim that the critical line has been overcome. If this was the case from some energy downwards, it would mean in fact that in that region, where a hadronic kinetic model is perfectly able to reproduce the data, critical line could not be located by studying hadron production in nuclear collisions.

The hadronic observables which can be used to investigate the phase transition are in principle many. It has been proposed to use fluctuations of conserved charges [8, 9] for they can be directly calculated in lattice QCD, unlike hadronic multiplicities, hence comparable with measurements and used to determine T and μ_B if the system has reached a point of equilibrium. However, multiplicities are first moments and, as such, far more robust observables against spurious effects. Indeed, fluctuations are strongly affected by both the effect of conservation laws [10] and finite acceptance [11], so that the interpretation of measurements requires much care and the subtraction of non-thermodynamic contribution can be a challenging task. For these reasons, we will focus on hadronic multiplicities and try to advocate them as still one of the best probes at our disposal to study and investigate the physical problem. We will summarize recent advances and outline what are, in our view, the next steps to be taken in the analysis to give a definite answer to the question.

¹ It is worth pointing out here that the strangeness undersaturation is still observed in nuclear collisions at high energy but it can be accounted for by residual nucleon-nucleon collisions nearby the outer edge of the nuclear overlapping region (core-corona model [6,7]).

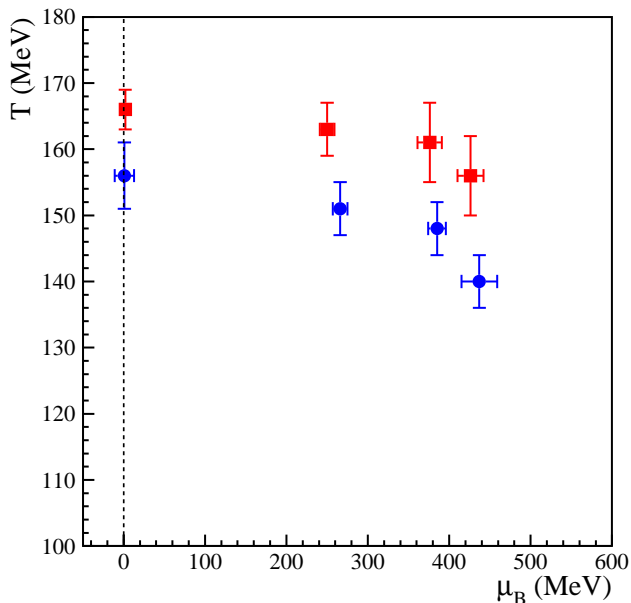


Fig. 1. (color online). Temperature and baryon-chemical potential of the hadronic system produced in central heavy ion collisions. Blue dots indicate chemical freeze-out points whereas red squares show the reconstructed LCEP's using UrQMD afterburner (taken from table in ref. [17])

2 Hadronization, statistical model and recent advances

As has been mentioned, a statistical *ansatz* is able to satisfactorily reproduce the measured hadronic yields, both in elementary [12] and in relativistic nucleus-nucleus collisions [13]. This has led to the formulation of the statistical hadronization model which, in a nutshell, assumes that hadrons are emitted from the fireball source at (almost) full chemical equilibrium. The reason of such a success, unexpected in elementary collisions, as well as the identity of the fitted temperature in all kinds of collisions, has been debated for a long time (see refs. [14,5] for a summary). In practice, one can take advantage of this phenomenon to locate the parton-hadron coexistence line of QCD matter in the (T, μ_B) plane.

The temperature determined by fitting the hadronic multiplicities is actually the one at which hadrons cease inelastic interaction, the so-called "chemical freeze-out" temperature. In principle this may differ from the QCD transition temperature if hadrons, after their formation, keep interacting inelastically. This is, clearly, not the case in elementary e^+e^- annihilation to hadrons but it could become relevant in the high multiplicity final state of AA collisions. Different reactions could then freeze-out at different times, in inverse order of inelastic cross section, so that this stage of the fireball source expansion, dubbed as "afterburning", would generally imply deviations from full chemical equilibrium of the hadronic species [15]. In the

standard statistical model analysis such effects were assumed to be negligibly small, and that, therefore, the temperature and baryon chemical potential yielded an ideal snapshot of the fireball dynamical trajectory, at or near QCD hadronization.

However, recently, we have demonstrated that afterburning, albeit being a correction to the leading statistical behaviour, ought to be taken into account as it implies a considerable improvement in the fit quality and - more importantly - a sizeable increase of the chemical freeze-out temperatures [16,17,18]. Similar improvements in the agreement between data and model were reported in ref. [19]. The underlying physical picture is as follows: the hadronization process (likely to coincide with the crossing of critical line) entails a primordial chemical equilibrium of multiplicities which is then distorted by the following stage of hadronic inelastic collisions before chemical freeze-out. This stage has a sizeable dependence on the geometry of the collision, the colliding nuclei and on their energy. The goal of the fit is to reconstruct the primordial chemical equilibrium point (defined as the *latest chemical equilibrium point* LCEP). The LCEP's are likely to coincide with the hadronization, hence with the a point on the critical line and if the fit is successful, with no evidence of an extra strangeness suppression other than that related to corona collisions, we can reasonably state that the critical line has been overcome.

The core method of the aforementioned analyses - described in detail in refs. [17,18] was to calculate particle multiplicities at the LCEP with the Cooper-Frye prescription and, thereafter, to let particle interact till freeze-out with the UrQMD transport code [20], to get a quantitative estimate of the influence of the rescattering stage. This approach worked very well for the most central collisions from LHC down to SPS energy (where data collected by the NA49 experiment were used [21]), providing an indication that the critical line has indeed been crossed down to $\sqrt{s_{NN}} = 7.6$ GeV, although a detailed analysis of the corona collisions is still missing. In fig. 1) we show our reconstructed LCEP's along with the uncorrected chemical freeze-out points. The LCEP's points define a sizeably flatter curve in the QCD phase diagram whose curvature seems to be in a better agreement with lattice calculations [22,23,24,25].

One can wonder whether it could be extended further down, where at some point it will have to fail, signalling that the critical line has not been attained. Unfortunately, the data from AGS in this respect does not allow firm conclusions, because the measured multiplicities are few and the full phase space measurements are even fewer. The present statistical model fits in this region [2] in the authors view, are thus not as reliable as those at energies higher than AGS, that is $\sqrt{s_{NN}} > 5$ GeV. For this reason, a detailed exploration of the energy range 2-10 GeV is compelling and accurate measurements of hadronic multiplicities are needed.

3 A task list

In order to establish an interval of energies where transition line has possibly been crossed, it is necessary to have a set of very accurate measurements on the experimental side and very accurate calculations on the theoretical side. Unfortunately, on both sides, it is not always possible to achieve the desired accuracy, nevertheless it is worth listing here the problems that will be encountered and the future demands.

From the experimental viewpoint, a measurement of the multiplicities of many species in full phase space besides midrapidity will be necessary. It is known that a cut at midrapidity artificially enhances strange particles and that it introduces more uncertainties on the quantitative effects of canonical suppression. This is a known problem in, e.g. the RHIC beam energy scan, where the use of exact strangeness conservation in the fit of midrapidity yields changes the slope of the chemical freeze-out temperature as a function of centrality [26]. Finally, for the sake of systematic consistency while changing the incident energy, it is essential to maintain the same set of hadronic species, covered in the analysis (ideally extending down to the small Ω hyperon yield).

In order to tune the hadronic models and to take into account corona effects, a measurement of multiplicities in pp (an possibly np and nn) collisions at the same energies and within the same kinematical windows of the heavy ion run will also be necessary. Of course, in this respect, the NA61/SHINE [27] pp data will be helpful, if taken at the same energy. For the same purpose, a measurement over a sufficiently large centrality range in the nuclear collisions will be crucial to check that hadron production is fully understood.

From a theoretical viewpoint, the endeavour will be a major one. The hadronic transport models will have to be coupled to the statistical hadronization (at high energy this happens through the Cooper-Frye prescription) as well as be used in a standalone mode [20, 28, 29, 30]. Statistical hadronization normally uses the hadron-resonance gas implementation, which amounts to disregard the contribution of the non-resonant hadronic interaction as well as higher order corrections. This is expected to be (and confirmed by lattice QCD) a very good one at low μ_B , but it is not yet clear if it will be as good at large μ_B , where the continuum may play a major role. Going beyond the hadron-resonance gas in the statistical model will be possibly needed, what will require a major theoretical and computational effort.

4 Conclusions

The precise measurement of hadronic multiplicities entailed a substantial progress in understanding hadronization and its relation with QCD over the last twenty years and it will continue to do so in the future. Therefore, we think that it will be a must for the NICA experimental programme to achieve complete and accurate sets of measurements of as many hadronic species as possible, at

various closely spaced energies. We wish to note, in passing, that a relatively narrow sequence of LCEP's points in the $T - \mu_B$ plane, gathered at closely spaced successive incident energies, might also exhibit a non-trivial, non-monotonic behaviour, as a consequence of the expansion trajectory focussing effect due to a critical point of QCD occurring in the thus covered interval of μ_B . This interesting proposal [31] has not been further elaborated theoretically, let alone tested experimentally.

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